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LAND USE

Life cycle assessment in the minerals and metals sector: a critical review of selected issues and challenges

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Abstract
Background, aim and scope The mining sector provides materials that are essential elements in a wide range of goods and services, which create value by meeting human needs. Mining and processing activities are an integral part of most complex material cycles so that the application of life cycle assessment (LCA) to minerals and metals has therefore gained prominence. In the past decade, increased use of LCA in the mineral and metal sector has advanced the scientific knowledge through the development of scientifically valid life cycle inventory databases. Though scientifically valid, LCA still needs to depend on several technical assumptions. In particular, measuring the environmental burden issues related to abiotic resource depletion, land use impacts and open-loop recycling within the LCA are widely debated issues. Also, incorporating spatial and temporal sensitivities in LCA, to make it a consistent scientific tool, is yet to be resolved. This article discusses existing LCA methods and proposed models on different issues in relation to minerals and metals sector.
Main features A critical review was conducted of existing LCA methods in the minerals and metals sector in relation to allocation issues related to indicators of land use impacts, abiotic resource depletion, allocation in open-loop recycling and the system expansions and accounting of spatial and temporal dimension in LCA practice.
Results Evolving a holistic view about these contentious issues will be presented with view for future LCA research in the minerals and metals industry. This extensive literature search uncovers many of the issues that require immediate attention from the LCA scientific community.
Discussion The methodological drawbacks, mainly problems with inconsistencies in LCA results for the same situation under different assumptions and issues related to data quality, are considered to be the shortcomings of current LCA. In the minerals and metals sector, it is important to increase the objectivity of LCA by way of fixing those uncertainties, for example, in the LCA of the minerals and metals sector, whether the land use has to be considered in detail or at a coarse level. In regard to abiotic resource characterisation, the weighting and time scales to be considered become a very critical issue of judgement. And, in the case of open-loop recycling, which model will best satisfy all the stake holders? How the temporal and spatial dimensions should be incorporated into LCA is one of the biggest challenges ahead of all those who are concerned. Addressing these issues shall enable LCA to be used as a policy tool in environmental decision-making. There has been enormous debate with respect to on land use impacts, abiotic resource depletion, open-loop recycling and spatial and temporal dimensions, and these debates remain unresolved. Discussions aimed at bringing consen-

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sus amongst all the stake holders involved in LCA (i.e. industry, academia, consulting organisations and government) will be presented and discussed. In addition, a commentary of different points of view on these issues will be presented.

Conclusions This review shall bring into perspective some of those contentious issues that are widely debated by many researchers. The possible future directions proposed by researchers across the globe shall be presented. Finally, authors conclude with their views on the prospects of LCA for future research endeavours.

Recommendations and outlook Specific LCA issues of minerals and metals need to be investigated further to gain more understanding. To facilitate the future use of LCA as a policy tool in the minerals and metals sector, it is important to increase the objectivity with more scientific validity. Therefore, it is essential that the issues discussed in this paper are addressed to a great detail.

Keywords Abiotic resource · Allocation and spatial variability and temporal differentiation · Depletion · Land use · LCA · Minerals and metals sector · Open-loop

Background, aim and scope

One of the most sought-after tools in the industrial ecology tool box is life cycle assessment (LCA). LCA has proven to be a valuable tool for evaluating the potential environmental impact of products and materials. This is the reason why, in the past few decades, many companies are internalising LCA as one of the important tools in evaluating their environmental performance. This increased global interest in using LCA and consequent benefits associated with it as a tool for even achieving environmental stewardship have attracted the attention of the mineral sector.

The mining sector provides materials that are essential elements in a wide range of goods and services, which create value by meeting human needs. Mining and processing activities are an integral part of most complex material cycles, and therefore, the application of LCA to minerals and metals has gained prominence. In the past decade, increased use of LCA in the mineral and metal sector has advanced scientific knowledge through the development of scientifically valid life cycle inventory databases. Though scientifically valid, LCA still needs to depend on several technical assumptions. Figure 1 illustrates how the LCA becomes an ambiguous tool in its current state.

In this paper, a critical review of selected issues and challenges concerning LCA in general and issues related to the mining and metal sector in particular are presented. However, there may be several other issues such as issues relating to exhaustive assessment of metals in LCA, allocation for co-products, choosing boundaries, collecting primary data, etc. have not been discussed in this paper. For example, measuring the environmental burden issues related to abiotic resource depletion, land use impacts and open-loop recycling within the LCA is a widely debated issue. Also, incorporating spatial and temporal sensitivities in LCA to make it a more consistent scientific tool are yet to be resolved. This review article discusses existing LCA methods and proposed models on selected issues in relation to the minerals and metals sector.

Overview of life cycle assessment

LCA is a technique used in environmental analysis of potential environmental impacts of any product or process over its entire life cycle, from raw material acquisition to ultimate disposal (International Organization for Standardization (ISO) 14040 2006a). However, it is still a fairly new tool as the methodology is still under development. From the time it was first used to the present, there have been several modifications/alterations in its structure, methodology and protocols. A schematic diagram of the classification of LCA is presented in Fig. 2. Accordingly, it is very important to know from the initial stage for what purpose an LCA is conducted.

LCA was developed directly from a desire to limit the energy used in manufacturing processes in the 1970s, especially in the manufacture of plastics, steel, pulp and paper and petroleum refining (Huppes 1996). However, until the early 1990s, no standardisation of methods was undertaken. One of the major limitations was the lack of objectivity, in the sense that when LCA was conducted under different approaches, there was a wide variation in results (see Fig. 1). One important problem that needs to be addressed is ‘brining harmony between the impacts predicted by LCA and the expected occurrence of actual impacts’. This calls for standardisation of LCA procedures (Huppes 1996). A summary of the historic developments is presented in Table 1. The result of this historical sequence of events has led to the publication of a series of international standards such as ISO 14040 (2006a) and ISO 14044 (2006b), which describe the essential elements of LCA studies. These have been amended from time to time, and a number of guides have been published. During LCA studies, the material and energy resources consumed and wastes emitted are accounted through the application of mass and energy balance checks, thus making it as a scientific tool. This holistic scientific tool considers the inclusion of both the environmental effects directly due to the processing of the object under study and the effects of processing other objects that allow for its production.

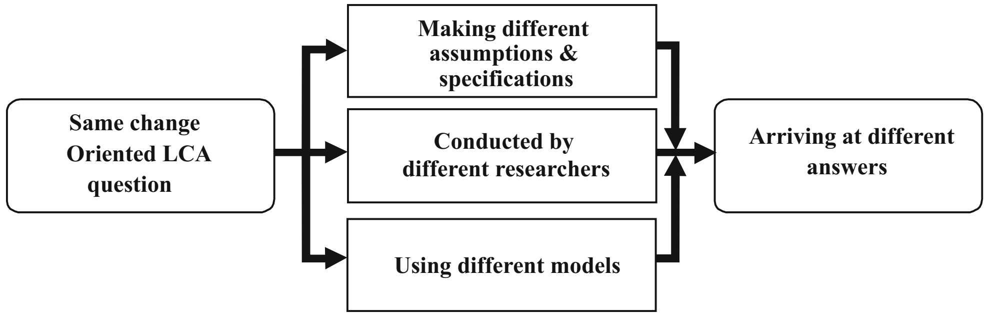

Fig. 1 Schematic representation of missing objectivity in current LCA

Current status of LCA research: a minerals sector perspective

The increased use of LCA has prompted companies to undertake extensive research and development work in this area, particularly with regards to generation and maintenance of life cycle inventories in respect to the mineral and metal sector. Metals and minerals have different characteristic features compared to other materials such as wood, paper and plastics, as is shown in Table 2. Understanding these important characteristics will open new insights and thus help in developing specific strategies. Of late, the mining and metal sector through International Council on Mining and Metals (ICMM) has become a founding partner of the UNEP/SETAC Life-cycle initiative (Dubreuil 2005). In the following sub-sections, we will present and discuss the areas of concern in current LCAs to the minerals and metal industries.

Land use impacts

Land provides support functions of life for both human and non-human life forms (Mila i Canals et al. 2007). Land use by the mining industry, though temporary in nature, leads to substantial impacts, particularly on biodiversity and on soil quality as a supplier of life support functions. In recent times, there has been an enormous debate on land use impact assessment in LCA, particularly in mining, which is a high land-demanding sector. Two SETAC working groups started to frame the issue of land use impacts (Udo de Haes 1996; Lindeijer et al. 2002). However, until now, no widely accepted assessment methodology has been developed to encompass the impacts due to mining land use into LCA.

Many references focus on suggesting indicators to include the effects of land use on biodiversity and biomass production (Köllner 2000; Schenck 2001; Weidema and Lindeijer 2001; Brentrup et al. 2002a, b; Bauer and Zapp 2004; Scholes and Biggs 2005). Until now, there is a debate going on as to what is the level of detail at which LCA should assess land use impacts. A coarse level assessment may allow the detection of hotspots from a life cycle perspective, whereas a more detailed assessment might allow the distinction between land management modes. In Table 3, we have summarised the suggested impact assessment models based on both midpoint and damage approaches (Jolliet et al. 2004). However, the practical implementation of such indicators is never checked with a consistent framework. This has led to the omission of land use impacts in LCAs, thus forcing many stakeholders to resort to other tools in addressing land use impacts.

Abiotic resource depletion

Resources are entities that are valued for the functionality that they deliver to human society. Therefore, quantification of resource depletion in LCA has been the topic of much debate. Until now, no definitive approaches for quantifying the effects in this impact category have been developed. However, there is a broad consensus on impact category indicators in life cycle impact assessment (LCIA) and their significant environmental issues (ISO 14040 2006a), but there seems to be less consensus on how significant the

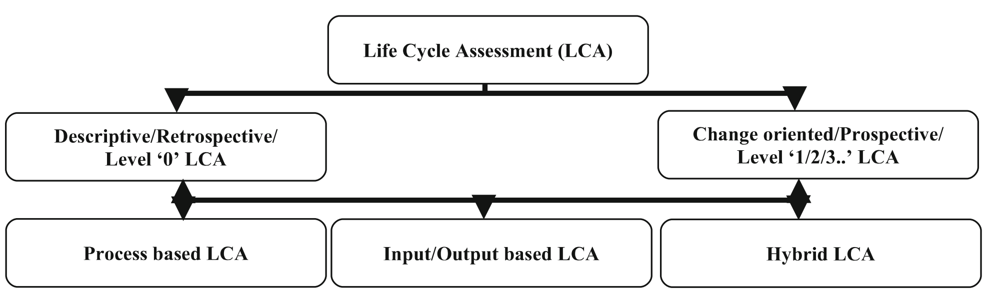

Fig. 2 Classification of LCA

Table 1 Historical landmarks driving the LCA moment

Year	Major events in LCA development as a science
1960s	LCA was performed by the Midwest Research Institute (MRI) (Giudice et al. 2006)
1970s	The US Department of Energy commissions' studies on 'Energy Analysis' titled 'Resources & Environmental Profile Analysis' (REPA) (Guinée 2002)
1980s	'Green Movement' in Europe brings focus back on emissions and the need for recycling. European industries study their pollution releases and begin comparing alternatives (Guinée 2002)
1989–1990	SETAC is first involved in LCA/The first ever SETAC workshop was held to define LCA (Guinée 2002)
1992	First Dutch guide on LCA was published (Guinée 2002)
1994	First time involvement of International Standards Organisation (ISO) (Giudice et al. 2006)
1995	UNEPs first involvement through publication first document—'LCA: what it is and how to do it'. Subsequently, in 1996 releasing 'Towards the Global Use of LCA' (Giudice et al. 2006)
1997	First ever ISO14040 standards series on LCA brought into force (Giudice et al. 2006)
2002	UNEP/SETAC Life Cycle Initiative began (Guinée 2002) International Council on Mining and Metals (ICMM) and Natural Resources Canada (NRCan) joined hands with UNEP-SETAC (Debreuil 2005)

problem of abiotic resource depletion is and to what extent it should be on the agenda of LCIA (Steen 2006). According to Steen, the existing methods for characterisation and weighting of abiotic resources appear to be based on following four types of problem definitions: (a) Mining cost will be a limiting factor; (b) collecting metals or other substances from low-grade sources is mainly an issue of energy; (c) scarcity is a major threat; and (d) environmental impacts from mining and processing of mineral resources are the main problem.

Impacts from resource use have been a prominent impact category in most environmental impact assessment methods for LCA developed since the early 1990s. Udo de Haes (2006) argues that resource management is viewed as crucial for LCA studies. In accordance with the general concerns of the broader public at the time, emphasis has been made on abiotic resources, specifically on energy and metallic minerals and on the extraction stage of the minerals' life cycle. The numerous methodologies proposed for the impact assessment of resource use were reviewed by the SETAC Working Group IA-2 (Lindeijer et al. 2002). Based on a suggestion by Finnveden (1996), the methodologies were categorised into four main approaches. Two out of four methodologies focus on current consumption, while two other types focus on future consequences. The major deficiency in these methodologies has been their lacking of ability to adequately reflect the loss in functionality related to their use.

For LCIA, various proposals have been made for impact categories and category indicators for abiotic resources. Several reviews are available, such as Lindfors et al. (1995), Weidema (2000), Guinée (2002), Finnveden

Table 2 Characteristics of main material families (modified from Young et al. 2001)

Characteristics	Details		
	Metals	Plastics	Wood and paper
Resource stock	Metal ore/minerals	Crude oil	Forests
Source	Lithosphere	Lithosphere	Biosphere
Extraction method	Mining: opencast/underground	Drilling and extraction	Harvest
Material structure	Elemental (metals/alloys)	Molecular	Cellular
Material renewal	Recyclable	Recyclable but quality degrades	Recyclable but quality degrades
Final fate	Elements are permanent and may remain for a long time	Combustion, degradation and landfill	Biodegradation, combustion and landfill
Losses	Corrosion, wear, process loss	May return to carbon cycle	May return to carbon cycle
Time scale of material stock	Theoretically unlimited	Days to years	Days to decades
Applications	Beverage cans, consumer products, auto components, motors, structures, etc.	Furniture, coatings, packaging, appliances and auto parts, etc.	Building, books/news papers, packaging and furniture, etc.

Table 3 Examples of impact pathways from land use including requirements of LCI information

Impact pathways		Category indicators	LCI modelling requirements
Soil quality	Natural environment	Should be explored according to the affected impact pathways. (*Endpoint/damage approach*)	To be investigated, according to the affected impact pathways (e.g. global warming, toxicity, etc.)
		Combinations of nine indicators, such as, pore volume; SOM; microbial activity, etc. (*problem oriented/midpoint approach*)	Effects due to agricultural activities on nine soil quality indicators (Oberholzer et al. 2006)
Biodiversity		Potentially disappeared fraction (PDF) of species. Potentially affected fraction (PAF) of species (*endpoint/damage approach*)	It may be worthwhile to work with these indicators as they are currently used by eco-toxicity categories (Jolliet et al. 2004)
		% of threatened vascular plant species in region (*problem-oriented/ midpoint approach*)	Description of the land use interventions to render a possible link to empirical data (number of vascular plant species per km^2) (Müller-Wenk 1998)
Biotic production potential (natural resources)		Surplus energy (*endpoint/damage approach*)	Requirements to restore soil quality through addition of organic amendments and other soil fractions (clay; sand); other interventions may include gaseous emissions from organic amendments (Milà i Canals et al. 2006)
		Eroded soil (*Problem-oriented/ midpoint approach*)	Calculated with empirical models of the soil-erosion process (e.g. RUSLE, MUSLE, USLE, etc.), requiring slope gradient, rainfall intensity, vegetation cove, soil type, etc.

(2005), Weidema et al. (2005), Brent and Hietkamp (2006) and Steen (2006). In principle, there are four types of indicators based on the following: (a) energy or mass; (b) relation of use to deposits; (c) future consequences of resource extractions; (d) exergy consumption or entropy production. Based on the discussion presented by Guinée (2002) and Strauss et al. (2006), the abiotic resource depletion impact assessment methods may be characterised into six groups as given in Table 4.

Stewart and Weidema (2005) have proposed a framework for assessment of impacts due to resource use. They considered both abiotic and biotic resources and to develop a consistent methodology for assessing the impact of the use of these resources. In this, they dealt specifically with the functional values of natural resources, as opposed to their intrinsic or existence values. It was argued that most abiotic resources have only functional value to humans, i.e. they are valuable because they enable us to achieve other goals that have intrinsic value, such as human welfare, human health or existence values of the natural environment. Hence, they proposed in the context of the framework developed the elements that require definition within an LCIA resource depletion model. These are a functionality indicator, an ultimate quality limit and backup technologies.

Table 4 Impact assessment methods of abiotic resources

Characterisation group	Assessment method
Group 1	Aggregation of natural resource extraction on mass basis
Group 2	No aggregation of mined abiotic resources depletion in the characterisation phase of LCIAs
Group 3	Aggregation and assessment based on energy impacts based on substitution of the current extraction process improved future processes.
Group 4	Aggregation and assessment based on the exergy or entropy content or change
Group 5	Aggregation and assessment based either on the quantity of resource that is ultimately available or the part of the reserve base that can be economically extracted and the extraction rate at the time of the assessment
Group 6	Aggregation and assessment based on the change in the anticipated environmental impact of the resource extraction process due to lower-grade deposits that have to be mined in the future

Allocation in open-loop recycling

In ISO 14044, allocation is defined as the partitioning of material and energy flows to or from an activity to the product system under study. However, environmental burdens, including land transformations, can also be partitioned in an allocation. According to ISO 14044, the open-loop recycling is defined as 'the recycling of a material from one product life cycle into another', whereas recycling within the product system is referred to as a closed-loop (ISO 14044 2006b). From the technical description point of view of an open-loop product system, the open-loop recycling is defined as 'a system where the material is recycled into other product systems and the material undergoes a change to its inherent properties'. From allocation of environmental burdens, the loop is considered to open when the material undergoes changes in its inherent properties (Fig. 3).

A multifunctional process is a unit process yielding more than one functional flow (Guinée 2002). For example, it may be a production process with more than one product or a waste management process dealing with more than one waste flow and/or a recycling process providing waste management as well as material production (Ekvall and Finnveden, 2001). Environmental burdens are defined as the resource demand, the emissions of pollutants, the waste generated and the land transformation caused by the technological activities.

A methodological allocation problem arises in the life cycle impact (LCI) when the product life cycle investigated includes inflows or outflows of recycled material. What share of the environmental burdens of the primary production, recycling and final waste management of the material should be allocated to the product investigated? (Ekvall and Tillman 1997), for example, if the primary production, recycling and final waste management of the material in the life cycle of the product investigated fulfil functions for other product life cycles.

Many solutions to the allocation problems have been suggested by different researchers (Boguski et al. 1994; Dubreuil 2007; Rydberg 1995; Klöpffer 1996; Ekvall and Tillman 1997; Kim et al. 1997; Newell and Field 1998; Azpagic and Clift 1999; Ekvall 2000; Birat et al. 2005). The choice of solution can have a decisive impact on the results of the LCI (Furuholt 1995; Rydberg 1995; Høgaas and Ohlsson 1998). The ISO also presented a standard for LCI—ISO 14044 (Box 1)—which included an allocation procedure (Huppes and Schneider 1994).

Box 1: ISO allocation procedure in multifunction processes (ISO 14044 2006b):

- Allocation should be avoided, wherever possible, either through division of the multifunction process into sub-processes, and collection of separate data for each sub-process, or through expansion of the systems investigated until the same functions are delivered by all systems compared.
- Where allocation cannot be avoided, the allocation should reflect the physical relationships between the environmental burdens and the functions, i.e., how the burdens are changed by quantitative changes in the functions delivered by the system.
- Where physical relationship alone cannot be used as the basis for allocation, the allocation should reflect other relationships between the environmental burdens and the functions.

The ISO procedure has been criticised because it does not take into account the fact that different approaches to the allocation problem result in different types of information (Ekvall and Finnveden 2001), nor does it take into account the relationship between the method and the study goal (Ekvall and Tillman 1997). The same ranking order of

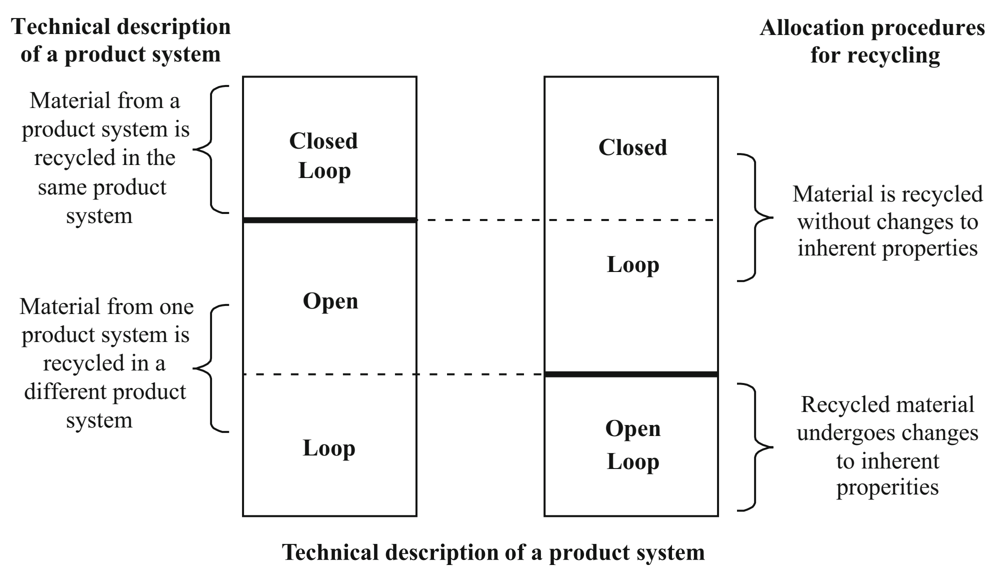

Fig. 3 Distinction between technical description of a product system and allocation for procedure for recycling (ISO 14044 2006b)

allocation methods is recommended for all LCA applications (ISO 14044 2006a, b). Hence, it may be necessary to revise the ISO procedure (Ekvall and Finnveden 2001). For the purpose of environmental modelling and decision-making involving recycling of metals, the metal industry has mandated the recycling principles (Box 2).

Box 2: Metal industry declaration on recycling principles states the following (Atherton 2007):

There are two approaches, currently in use, for assessing the benefits of recycling: (a) recycled content approach (b) end-of-life recycling approach. However, for all the purposes such as environmental modelling, decision-making and policy discussions involving recycling of metals, the metal industry endorses 'end-of-life' approach over the 'recycling content' approach.

Klöpffer (1996) has conducted an extensive review of allocation rules proposed and practised by LCA practitioners within the open literature. According to Klöpffer (1996), following three criteria can be used in establishing an arbitrary but reasonably consistent allocation rule:

- Mathematical neatness, internal logic, no double counting.
- Feasibility at a low level of information with regard to the actual use or origin of secondary raw materials.
- Justice and incentive for producers and users of secondary raw materials.

In a recent review by Curran (2007), it was observed that while system expansion is the most preferred approach in allocation due to the complicated model and requirement for more data, it was suggested to develop a range of allocation approaches aligned with different goals and scopes of the study. According to Curran (2007), different concepts used in allocation are tabulated below (Table 5).

Spatial and temporal issues in LCA

LCAs deal with complex, interwoven networks of industrial, commercial, household and waste management activities dispersed over many locations and spanning many decades (Guinée 2002). The mechanisms governing the dynamics are many and varied, and the mathematics governing them are non-linear and dynamic in nature. Spatial variabilities emerge from the obvious fluctuations in the real-life scenarios in the world. Even though there are natural variations between geographical sites, the environmental interventions are summed up in the impact assessment irrespective of their space (Bjorklund 2002). On the other hand, variations over time are relevant in both the inventory and impact assessment as the process and factors in the receiving environment vary naturally over short- and long-time scales (Bjorklund 2002).

So far, little attention has been paid in the literature to temporal differentiation in LCA (Guinée 2002). Owens (1996, 1997) criticised this lacuna of spatial and temporal considerations in the LCAs. This mentioned rates of emissions, duration and frequency of exposure and seasonal influences of temperature and sunlight as missing characteristics of time. Pleijel et al. (1999) studied the influences of climate and the time of the day of NOx and VOC releases on ozone formations in the troposphere in the context of LCA study although the biggest question yet to be addressed is how to incorporate this into a practical LCA methodology.

In recent years, the issue of spatial and temporal differentiation has been attracting attention (Potting and Hauschild 1997; Bare et al. 1999; Schulze and Matthies 1999; Potting 2000; Bjorklund 2002). However, no comprehensive approach for integration of spatial differentiation into LCA has been agreed upon. In order for it to be incorporated into LCAs, space-specific equivalence factors must be established. Potting (2000) started developing such factors for acidification and human toxicity although the study was restricted to Europe. Heijungs and Sleeswijk (1999) distinguish three dimensions in life cycle characterisation of toxic substances: fate, exposure and effect. The spatial differentiation of these variables may be performed independently. Potting and Hauschild (2006) argues that spatial differentiation is relevant for all non-global impact categories and further proposes three levels of spatial differentiation such as (a) site-generic (i.e. all sources are considered to contribute to the same generic receiving environment); (b) site-dependent (i.e. some spatial differentiation is performed where classes of sources and their receiving environment are distinguished from each other); (c) site-specific (i.e. detailed spatial differentiation is performed by considering sources at specific location).

It was argued by Huijbregts (1998) that spatial variability is introduced into LCA at two different phases, that is, during the inventory collection due to regional differences in emissions and also during the characterisation phase due to regional differences in environmental sensitivities. Similarly, the temporal variability is introduced in the inventory phase due to differences in yearly emission inventories and in the characterisation phase due to the different time horizons and due to changes in environmental characteristics over time. Table 6 provides an overview of the tools and approaches to address the spatial and temporal variabilities within LCA (Huijbregts 1998).

Discussion

LCA is increasingly used in the mineral and metal industry and is seen as a tool for materials choice and environmental

Table 5 Concepts of allocation used in LCA methodology

Allocation basis	Organisation	Description	Comments
Energy	GREET (US Department of Energy, i.e. USDE)	Follows a process where co-product value is measured by energy units. Easy to apply, predictable over time, minimises counter-productive incentives	Mere energy accounting is not able to heed important environmental effects like pollutant emissions
Mass	US EPA	States that no allocation basis is always applicable. But, the guide endorses *mass* basis	Proclaims that conservation of mass is based on chemical engineering, chemistry, physics and with reasonable modelling techniques
Economics	NREL (USDE) CML Guide	Follows the ISO hierarchy but recommends an economic basis	Remained at principles level. How exactly this has to be done has not been specified yet, therefore, still unclear about its procedure
		Economic allocation is advised for all detailed LCAs	Due to fluctuations in prices, results may vary
Other	EcoInvent eLCIe 2004	Avoids using system expansion. Allows for *choice* of basis	Economic allocation is used for almost all the emissions unless the CO_2 ones, which are based on carbon content and carbon balance
		Recognises the ISO standard and the need to allow flexibility	Flexibility in choosing, but lacks consistency

GREET greenhouse gases, regulated emissions and energy use in transport, *NREL* national renewable energy laboratory

decision-making with the goal of achieving sustainable development. This is evident from the very fact that the ICMM is continuously striving to facilitate the development of LCA protocols and guidance to increase their relevance to the minerals and metals sector. Accordingly, ICMM in collaboration with UNEP-SETAC life cycle initiative is involved in a project to improve the methodology currently being used with more scientific validity.

Although the majority of land use impacts are temporary, sometimes it is irreversible and leads to substantial impacts. In recent years, the land use impacts have received greater attention in LCA, but a consistent framework that brings consensus amongst all the stakeholders and development of robust method is still lacking. And, exclusion of land use impact issues will hamper the credibility of LCAs particularly in the context of mining as it damages the land to a very great extent. Hence, it should be borne in mind that the LCA results will be incomplete and become less credible as long as the land use impacts are not being incorporated. Therefore, until such a consistent framework based on the proposed indicators such as biodiversity, biotic production potential and ecological soil quality acceptable to all the stakeholders is established, the discussions relating to land use impacts in LCA needs to continue.

Table 6 Various tools available to address spatial and temporal inconsistency issues in LCAs

Sr. no.	Tools
1	Higher resolution models
2	Sensitivity analysis
3	Uncertainty importance analysis
4	Classical statistical analysis
5	Bayesian statistical analysis
6	Scenario modelling

Abiotic resources are raw materials or means for production or consumption activities. Damage to abiotic resources implies that the resources are destroyed through intended or unintended physical disintegration or dissipation, including weathering, wear and tear, sometimes exaggerated by pollution or lack of adequate protection or maintenance or intended or unintended chemical reactions (including combustion). The damage consists of the reduced availability of the corresponding type of resource to future generations. Though geologic studies indicate that quantity of most of the abiotic resources accessible for humans is extremely high for most of the abiotic resources, others consider the current reduction of the easily usable part of certain natural resources as not being negligible.

In 'Limits to growth', Meadows et al. (2005) identified that the increasing cost of resources is becoming a major problem for society during the first or second decade of the third millennium and their ideas were widely spread. Therefore, resource depletion needs to be considered in LCAs from the perspective of time, environmental and economic aspects of mineral extraction and future consequences of decreased availability of mineral resources for a region.

Our understanding of current global minerals consumption patterns is reasonably good. Therefore, when considering the scarcity of minerals, excluding dramatic changes in technology, it is possible to forecast how the future

resource demand and use will change. Hence, it is possible to define scarcity in the context of minerals from the time perspective for any region. However, there are different thoughts that have been doing the rounds in the scientific circles within LCA regarding which time perspective to apply when defining scarcity of minerals. One school of thought is that abiotic resources scarcity is perceived to be the decreasing concentrations of mineral resources at some time in the future, therefore it is an issue to be addressed in LCA, whereas another school of thought argues that backup technologies will take care of decreased mineral concentrations, and hence, mineral depletion may not be an issue. However, the European Commission developed a strategy with a 25-year perspective (Steen 2006).

Another important dimension in evaluating the impacts due to resource depletion is to consider both environment and economic aspects. As mineral extraction in some regions is viewed from a socio-economic point of view rather than just an economic point of view, this opens an entirely different perspective of quality of life in regions depending on mineral extraction. As the discussion still remains inconclusive, further debate is needed.

In general, another important methodological problem that exists in current LCA is allocation of environmental burdens in recycling of material and energy, in particular allocation in open-loop recycling. Metals are highly recyclable, and in fact, a large percentage of metallic material is effectively recycled. In a way, ‘the cities of today are the mines of tomorrow’ assumes greater importance particularly in the context of metals recycling (Jacobs 1969). Recycling plays a very important role in these modern times of perceived resource scarcity. Hence, applying LCA to model metals recycling has to be performed with greater caution as metal recycling offsets the primary production process and their associated environmental impacts as this collected metal scrap is converted to new material of equal or similar quality through metallurgical processes. Perhaps even more importantly, recycled metal substitutes or displaces the necessity to mine new metal.

As many of the researchers have observed that current ISO allocation procedure is inadequate, where recycling is not directly identified as an issue, the practitioner is thereby left free to choose the method which can have decisive effects on the results of an LCA. And, as such, different practitioners use different methods, thereby making the LCA vague. However, system expansion is identical to the commodity-technology assumption that was used for a long time in the production of input–output matrices from supply-use matrices. And, therefore, it can be elegantly implemented consistently across a full LCI database, simply by structuring the data in a supply-use framework and using the commodity-technology assumption. An example of metal industries in general and steel in particular is explained in Box 3.

Box 3: Example of metal industries case of recycling-with special reference to steel: (WSA 2008)

From the individual steel company stand point of view steel recycling appears to be open loop because the scrap generated on account of end-of-life of a product going back to closest smelters. And, for example, an old structural steel product to be melted down to produce a car, and then, when this car is recycled at its end-of-life, is melted down to produce structural beam, container or any other product. However, in the majority of cases, steel scrap recycling involves re-melting to produce new steels with little or no change in its inherent properties and, thus, for most cases of recycling can be regarded as being closed loop. In this respect, the ISO standards state that ‘in such cases the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials’. This guidance provides the basis for the ‘closed material loop’ recycling methodology.

Due to absence of spatial and temporal differentiation in LCA, prediction of environmental concentrations becomes difficult. Consequently, it becomes difficult to evaluate whether a no-effect level is exceeded. Usually, most LCIA methods make only limited use of spatial and temporal information because they predict concentration increases rather than full concentrations. This is one of the reasons why some LCA studies show poor accordance between predicted and actual environmental impacts of non-global nature. Consequently, it becomes difficult to make a judgement whether or not the threshold is exceeded, particularly for human toxicity assessment. This character affects the credibility of LCA. The reliability and validity of LCA results can be greatly improved by introducing the spatial and temporal differentiation. Although the location and time-specific data is rarely available for all the processes within a product life cycle, the spatially differentiated assessment may be preferable for those processes for which the required information is available. Therefore, it is highly recommended to direct the efforts in gathering and generating more time- and location-specific databases. Also, it is important to consider developing a time-dependent analysis LCA model, where the functional unit can be altered with time.

Conclusions

In this paper, we have conducted a critical review of LCA literature, in general, and literature related to mineral and metal sectors, in particular, with respect to abiotic resource depletion, land use impacts, open-loop recycling and spatial and temporal issues within the LCA. And, it was found that

there has been enormous debate happening within LCA community over these contentious issues, yet the methodology remains in a constant flux though LCA is being widely applied and extensively used within minerals and metal industries for production and product improvement. The power of LCA would increase significantly if it was validated by fixing these gaps in current methodology and knowledge. And, it is imperative that the scientific community addresses the issues discussed in this paper at the earliest to foster the process of acceptability and applicability in the minerals and metal sector.

As highlighted in this paper, issues discussed in this paper are of interest to LCA, in general, and important to mining and metals industries, in particular. Also, these issues have not been adequately addressed in LCAs' current form. These issues also bring about inconsistency in LCA practice and hence the results and their interpretation, etc.

Recommendations and perspectives

Minerals and metal-specific LCA issues need to be investigated further to gain more understanding. To facilitate the use of LCA as a policy tool in the minerals and metals sector, in the coming years, it is important to increase the objectivity with more scientific validity. Therefore, it is essential that the issues discussed in this paper are addressed to a great detail at the earliest possible. This would not only increase the credibility of LCA but also enhances its use across the sector as a policy tool and facilitates an achievement of sustainable development.

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